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Temporal strategy and performance during a fatiguing short-cycle repetitive task

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This study investigated temporal changes in movement strategy and performance during fatiguing short-cycle work. Eighteen participants performed six 7-min work blocks with repetitive reaching movements at 0.5 Hz, each followed by a 5.5-min rest break for a total duration of 1 h. Electromyography (EMG) was collected continuously from the upper trapezius muscle, the temporal movement strategy and timing errors were obtained on a cycle-to-cycle basis, and perceived fatigue was rated before and after each work block. Clear signs of fatigue according to subjective ratings and EMG manifestations developed within each work block, as well as during the entire hour. For most participants, timing errors gradually increased, as did the waiting time at the near target. Changes in temporal movement strategy were negatively correlated with changes in the level and variability of EMG, suggesting that an adaptive temporal strategy offset the development of unstable motor solutions in this fatiguing, short-cycle work.

Practitioner Summary: Sustained performance of operators is essential to maintain competitiveness. In this study of repetitive work, participants gradually changed their temporal movement strategy, for possibly alleviating the effects of fatigue. This suggests that in order to effectively counteract fatigue and sustain performance, industrial production should allow extensive spatial and temporal flexibility.

Keywords: temporal movement strategy; performance; fatigue; repetitive work; EMG

1. Introduction

More than 60% of the European working population reports to perform repetitive hand or arm movements during more than 25% of their working time (Eurofound 2010). Muscle fatigue may develop during repetitive work requiring low or moderate force (e.g. Mathiassen and Winkel 1996, Nussbaum 2001), and has been proposed to be an important precursor to the development of neck and shoulder muscle disorders (e.g. Rempel *et al.* 1992, Takala 2002). Therefore, studies of the development and effects of fatigue during repetitive work are justified as part of the efforts to develop guidance on how to prevent disorders.

Several studies have suggested an association between fatigue development and temporal motor variability. More temporal variability in the EMG amplitude of back muscles (Dieën van *et al.* 2009) and more spatio-temporal variability of the EMG amplitude within the trapezius muscle (Farina *et al.* 2008) have been shown to be associated with slower development of electromyographic manifestations of fatigue. Dieën van *et al.* (1993) showed that people with a more alternating activation of different parts of the erector spinae muscle had longer endurance times in isometric back extensions; similarly Palmerud *et al.* (1998) suggested that load sharing between synergistic shoulder muscles might eliminate or delay muscle fatigue development. Recent studies confirm that motor strategies, including movement patterns, may change due to, or in order to counteract fatigue. Kinematic changes with time have been shown in repetitive throwing (Forestier and Nougier 1998, Hufnuss *et al.* 2006), hammering (Côté *et al.* 2005, 2008), sawing (Côté *et al.* 2002, Gates and Dingwell 2008) and reaching (Fuller *et al.* 2009, 2011, Lomond and Côté 2010). As an example, Côté *et al.* (2002) demonstrated that the movement amplitude of the elbow decreased during repeated sawing, compensated by a lower and more forward shoulder position and an increase in shoulder, wrist and trunk movement amplitudes.

Since fatigue does, by definition, imply a decrease in the capacity to generate muscle force, it could be expected to have a negative influence on task performance in many situations relevant to working life. Earlier

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studies, however, have shown inconsistent effects of fatigue on performance. In a tracking task, performance in terms of percentage time on target was not affected after a fatigue protocol (Selen *et al.* 2007), whereas Huysmans *et al.* (2008) showed a decrease in performance during a similar task. Also studies of activities closer to real occupational tasks have shown conflicting effects of fatigue. Force output and movement frequency were significantly affected by fatigue in sawing tasks (Hammarskjöld and Harms-Ringdahl 1992, Côté *et al.* 2008), whereas other studies of repetitive short-cycle activities did not find performance, in terms of movement time, trajectory, and timing errors, to be decreased (Côté *et al.* 2002, 2005, Gates and Dingwell 2008, 2010). These conflicting results may not only be explained by the difference in outcome parameters (Hoffman *et al.* 1992), but also by a fast recovery to normal capacity (Evans *et al.* 2003), and alterations in movement patterns that allow maintenance of performance in spite of fatigue (e.g. Gates and Dingwell 2008, Côté *et al.* 2002, Fuller *et al.* 2011). The fact that movement patterns may change in both spatial and temporal structure while performance is maintained has been shown in several studies of occupational relevance (Madeleine *et al.* 2008a,b, Dempsey *et al.* 2010, Lomond and Côté 2010).

Most of the studies investigating kinematics and performance during fatigue used another exercise protocol to induce fatigue than that used for evaluating its effects. As an example, Hufnagel *et al.* (2006), Huysmans *et al.* (2008) and Côté *et al.* (2002) all used sustained isometric contractions at high relative forces to quickly bring on considerable fatigue. A realistic temporal load pattern, including rest breaks, is rarely applied, neither for inducing fatigue nor for evaluating its effects (e.g. Gates and Dingwell 2008).

Thus, to our knowledge, the development across time of temporal movement adaptations during prolonged repetitive work has not been reported before, including the possible relationships between such motor adaptations and the development of fatigue and performance.

In the current study, we investigated performance and temporal strategy of movement in a fatiguing short-cycle repetitive reaching task with intermittent rest breaks performed for 1 h. We addressed the following research questions:

- (1) Does the temporal movement strategy and performance change during one hour of fatiguing repetitive work?
- (2) If present, are these changes correlated with changes in muscle activation, as measured by the level and variability of the electromyographic signal from the trapezius muscle?

2. Method

2.1. Subjects

Eighteen healthy, male subjects (14 right-handed and four left-handed, mean age 24.2 (SD 4.3) years, weight 79.8 (SD 10.4) kg, height 183.5 (SD 3.4) cm, BMI 23.7 (SD 3.0) kg/m²) volunteered to participate in the study. Exclusion criteria were disorders or pain in the neck, shoulders and arms. Furthermore, subjects who had surgery or trauma in the neck, back or shoulders or fracture or dislocation in the neck or shoulders were excluded. Subjects refrained from smoking and coffee intake 30 min before the experiment and were asked to avoid physical exercise during the two preceding days. All subjects gave their written informed consent prior to the start of the study and the study was approved by the Regional Ethical Review Board in Uppsala.

2.2. Procedure

The subjects performed a 1-h repetitive arm reaching task, as part of another study devoted to investigate effects of combining mental and physical loads (Mathiassen *et al.* 2008). In the main study, three mental load conditions of different complexity were introduced in breaks between blocks of the repetitive task, in experiments separated by at least one week. Only data from the easiest mental load condition were used in the current study. A training session was performed one day before the experiment to ensure familiarity with the methods and the task, and to offset a learning effect across trials. The training was continued until a stable work rhythm was achieved, or for a minimum of 3 min; i.e. about 90 work cycles (see below). All sessions were performed in a laboratory at a constant ambient temperature of 22°C.

2.3. Work task

Six consecutive work blocks were performed, each consisting of 7 min performing the repetitive task and a five and one-half minute rest break. During the rest break, subjects performed a memory test in which they were presented

letters on a computer screen in front of them, and asked at irregular intervals to recall the last presented letter. The work task was performed with the dominant hand while the other arm was resting on the table in a prescribed position.

The repetitive work, illustrated in Figure 1, consisted of moving a 300 g manipulandum held in the right hand (handle diameter 3 cm, outside dimensions: 0.09 m \times 0.06 m \times 0.12 m) between two targets at a frequency of 0.5 Hz (cycle time 2 s), as guided by a 1 Hz metronome signal. Subjects were asked to hit the targets in synchrony with the metronome signals, while they were free to choose their own timing strategy and work technique within each half-cycle, between the metronome signals. The upper target was located at shoulder height and at a distance corresponding to an elbow angle of 160° to avoid maximum stretching of the arm. The subject's sitting posture (knee angle at 90°), distance between upper body and table (10 cm) and working height (table surface 1 cm under elbow height with relaxed shoulders) were standardised according to anthropometrics. Each of the targets was equipped with an electrical connector, which was activated whenever the manipulandum touched the target.

2.4. Measurements

2.4.1. Surface EMG

Electromyography from the right trapezius, pars descendens was measured by a BioPac MP150 System (BIOPAC Systems Inc, Santa Barbara, CA USA) and amplified with BioPac EMG100C modules (BIOPAC Systems Inc, Santa Barbara, CA USA). Pre-gelled bipolar Ag/AgCl surface electrodes (AMBU Neuroline 720, Baltorpbakken 13, DK-2750 Ballerup) were placed 2 cm lateral to the mid-point between C7 and the acromion according to Mathiassen *et al.* (1995), using an inter-electrode distance of 25 mm. A reference electrode was placed on the C7 spinous process. Prior to the electrode placement, the skin area was shaved, scrubbed and cleaned with alcohol and it was checked that the impedance was below 5 k Ω . The raw EMG signal was visually inspected to check its quality. Electromyography signals were continuously sampled during the entire work block, band-pass filtered (10–500 Hz) and AD converted (16 bits at 2000 Hz). Data were analysed using Spike2 software (Version 6, Cambridge Electronic Devices). For each half-cycle of work (1 s), the average EMG amplitude was expressed in terms of the RMS value of the signal (Figure 2). The mean power frequency (MPF) of the signal was calculated using Welch's method (Welch 1967). Electromyography amplitudes were normalised (%RVE) using the RMS EMG amplitude during a 15s reference contraction with the arms abducted at an angle of 90 degrees (Suurkula and Hägg 1987). This isometric reference contraction was performed prior to the first work block while the subjects were sitting in their chair. The position of the arms was visually controlled by the experimenter.

The EMG signal is commonly interpreted to indicate fatigue when its frequency content decreases while, at the same time, the amplitude increases (Basmajian and De Luca 1985, Hägg *et al.* 2000). Possible EMG manifestations

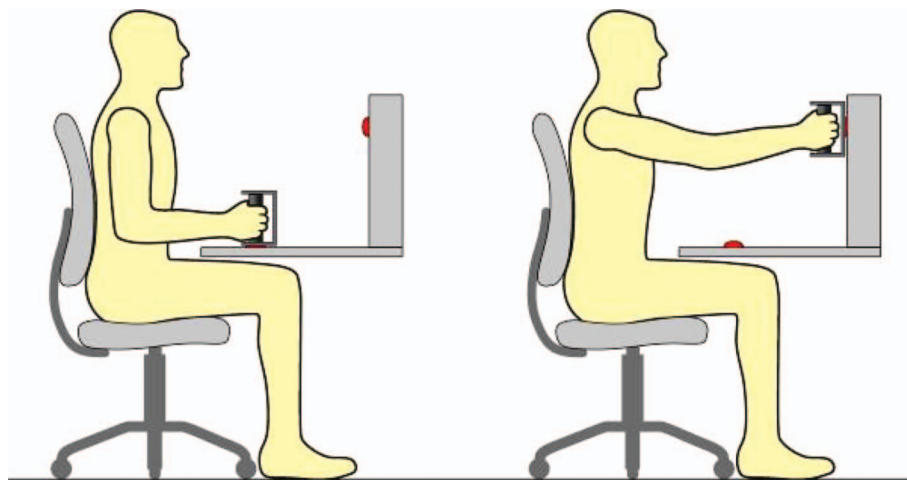


Figure 1. Workstation setup. Participants moved the manipulandum upwards from the lower target (left) to the upper target (right) with a predetermined time allowance of 1 s, and vice versa for the downward direction.

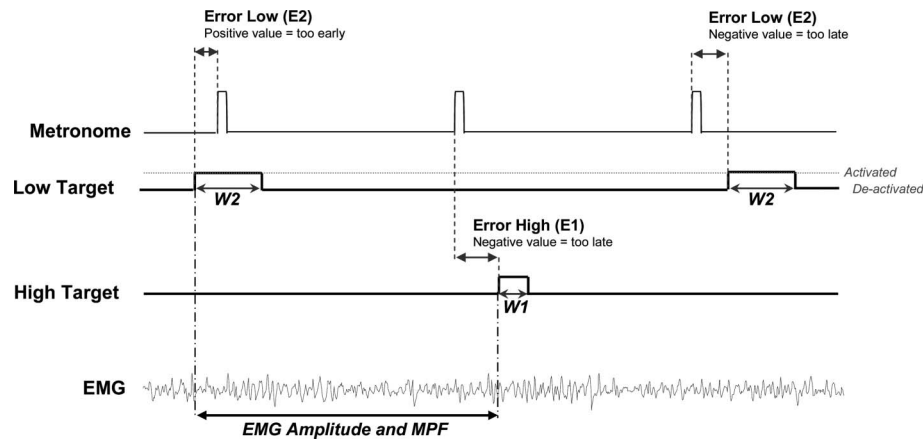


Figure 2. Timing, performance and EMG variables obtained for every work cycle. Waiting time (temporal strategy) at the high (W1) and low (W2) target was registered as long as the connector was activated. The timing error (performance) at the high target (E1) and low target (E2) was defined as the time difference between the metronome beat and the first touch of the target. EMG parameters were calculated as averages across each half-cycle.

of fatigue were addressed by comparing the average amplitude and MPF of the first 30 cycles of each work block ('early') with that of the last 30 cycles ('late'). In addition to average values, cycle-to-cycle variability in the EMG amplitude across these cycles was assessed in terms of the median absolute deviation (MAD), as described by Shevlyakov and Vilchevski (2002).

2.4.2. Perceived fatigue

Perceived muscle fatigue in the neck and shoulder area was rated before ('pre') and after ('post') every work block, using the Borg CR-10 scale (Borg 1982). The participant was acquainted with the Borg scale during the training session.

2.4.3. Temporal strategy and performance

The following parameters were obtained for every work cycle on basis of the signal from the target connectors (Figure 2):

- Temporal strategy, measured by the waiting time at the high (W1) and low target (W2) in seconds.
- Performance, expressed in terms of timing error. The timing error was defined as the time difference in seconds between the metronome beats and the corresponding first touch of the upper (E1) and lower (E2) target connectors. Positive timing errors indicated that participants were ahead of the metronome beat while negative indicated a late arrival to the target.

The average and cycle-to-cycle variability (MAD values) of waiting times and timing errors were calculated for the first 30 cycles of each work block ('early') and the last 30 cycles of that work block ('late'). Values were obtained for each movement direction separately.

2.5. Statistics

Data inspection indicated that neither EMG, performance nor timing data deviated from normal distributions. As the frequency distribution of perceived fatigue at a group level was considerably skewed, a logarithmic transformation was performed on the fatigue ratings. Development of perceived fatigue over time was examined using a two-way ANOVA for repeated measures with work block (1–6) and time (pre/post) as independent variables. Changes across time in EMG amplitude, MPF and EMG amplitude variability were analysed using a three-way ANOVA for repeated measures with direction (up/down), work block (1–6) and time-in-block (early/late) as independent variables. To examine changes in performance and temporal strategy, a similar three-way repeated

measures ANOVA was applied with the independent variables position (high/low target), work block (1–6) and time-in-block (early/late).

Degrees of freedom in the repeated measures ANOVAs were adjusted using Greenhouse–Geisser's epsilon to compensate for the effects of possible violations of the sphericity assumption (Twisk 2003). Interaction effects were post-hoc tested using a one-way ANOVA for repeated measures or student *t*-tests.

Associations between changes in EMG levels, EMG variability, temporal strategy and performance across participants were investigated in both movement directions separately using Pearson's product moment correlation coefficient (*r*). Changes in all parameters were defined as the difference between the 'early' cycles in the first work block and the 'late' cycles in the last work block.

3. Results

Ideally the protocol would result in 210 work cycles per work block. However due to technical problems with the experimental setup, on average 207 (SD = 2.5) work cycles were accepted per work block and used for further analysis.

3.1. Perceived fatigue and EMG

Fatigue gradually developed within and across work blocks as shown by the perceived fatigue ratings (Figure 3) and the EMG indicators of fatigue presented in Table 1. Perceived fatigue significantly increased during the 1-h task as indicated by a main effect of work block ($F(3.9) = 22.6$, $p < 0.001$). Furthermore, a significant increase ($F(1.0) = 121.6$, $p < 0.001$) in perceived fatigue was found within work blocks.

Similar findings were obtained for EMG amplitude and MPF (Table 1). Electromyography amplitude increased significantly within each block, as showed by the significant main effect of time-in-block (i.e. early vs. late in block). In the first work block, the EMG amplitude in the upward direction increased by 29% whereas the increase in the last work block was 24%. Smaller increases were found in the downward direction (11% and 15%). As shown by the main effect of work block (Table 1), the EMG amplitude even increased across work blocks over the 1-h period for both the upward and downward movement.

A significant effect of time-in-block (early vs. late in work block) was also found for the MPF (Table 1), indicating a decrease of the MPF within work blocks for both movement directions. However, no significant change of the MPF was found across work blocks, suggesting that the overall MPF had not changed after one hour.

Electromyography amplitude cycle-to-cycle variability increased significantly during the 1-h task (Table 1). Furthermore, EMG variability increased within all work blocks, as shown by the significant effect of time-in-block.

3.2. Temporal movement strategy and performance

As illustrated in Figure 4, the average waiting time early in the first block at the lower and upper target were 0.23 s (SD between subject 0.01) and 0.17 s (SD 0.06) and, respectively. The corresponding cycle-to-cycle variability in waiting time was lower at the upper (0.015 s) than at the lower target (0.025 s).

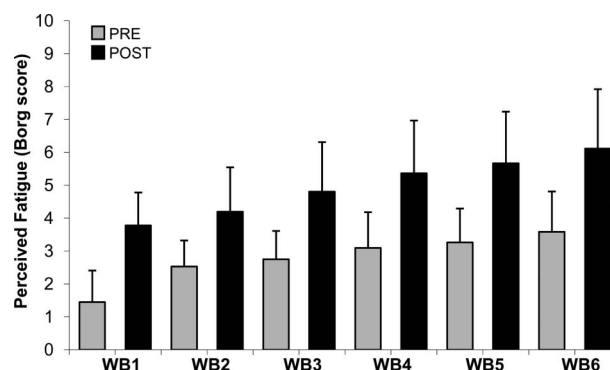


Figure 3. Perceived fatigue before (grey) and after (black) each of the 6 work blocks (WB1-WB6). Error bars show the standard deviation between participants.

A main effect of position showed that the average waiting time at the upper target (i.e. W1 in Figure 2) was significantly shorter than at the lower target (i.e. W2 in Figure 2). The effects of position and work block interacted significantly (Table 2). Post-hoc testing indicated a significant decrease of waiting time across work blocks at the upper target but no significant change for the lower target. Furthermore, a significant interaction effect between position and time-in-block was found. Post-hoc testing demonstrated a significant increase in waiting time within work blocks at the lower target ($t(17) = 2.2$, $p = 0.045$), whereas waiting time did not significantly change within work blocks at the upper target. The cycle-to-cycle variability of the waiting time did not change significantly within ($p = 0.85$) or across ($p = 0.72$) work blocks.

The average timing errors early in the first work block were 0.07s (SD between subjects 0.06) and 0.03s (SD 0.07) at the lower and upper target, respectively. This difference was significant for all work blocks (Table 2). Timing errors increased over the course of all work blocks (Figure 5), as shown by the significant main effect of work block. Although the average timing errors at the upper target were positive, indicating that participants arrived too early, 4

Table 1. Early and late values for the EMG variables (amplitude, MPF and amplitude variability) in the first and last work block and for both the upwards and downward movement direction.

		First work block M (SD)	Last work block M (SD)	Main effect work block (1–6)			Main effect time- in-block (early-late)		
				df	F	p	df	F	p
EMG amplitude up (%RVE)	Early	50.4 (15.3)	59.6 (16.5)	2.4	9.8	<0.001	1.0	64.8	<0.001
	Late	65.1 (17.6)	74.0 (22.7)						
EMG amplitude down (%RVE)	Early	41.9 (14.6)	45.5 (14.2)	1.4	1.1	0.34	1.0	14.5	0.001
	Late	46.4 (13.1)	52.5 (15.2)						
EMG MPF up (Hz)	Early	64.8 (8.0)	66.1 (10.4)	3.0	5.9	0.002	1.0	12.6	0.002
	Late	64.2 (7.9)	64.2 (9.2)						
EMG MPF down (Hz)	Early	63.5 (7.7)	64.9 (10.2)	3.0	5.9	0.002	1.0	12.6	0.002
	Late	61.8 (8.0)	61.9 (9.9)						
EMG amplitude variability up (MAD)	Early	3.42 (1.4)	4.55 (2.6)	3.0	5.9	0.002	1.0	12.6	0.002
	Late	4.25 (1.3)	5.99 (2.3)						
EMG amplitude variability down (MAD)	Early	3.46 (1.7)	3.98 (1.7)	3.0	5.9	0.002	1.0	12.6	0.002
	Late	3.76 (0.9)	4.24 (1.8)						

Note: Statistical results for pooled up and down values are presented for the main effects of work block and time-in-block. Significant results ($p < 0.05$) are boldfaced.

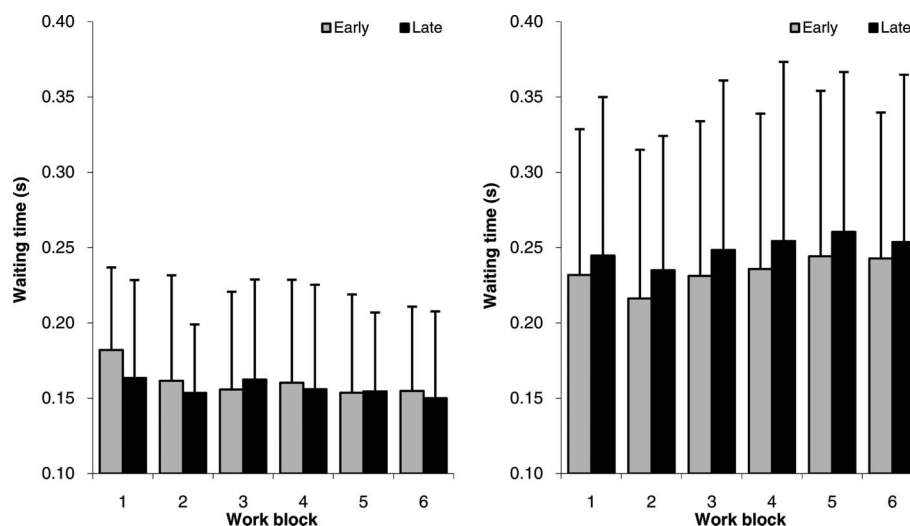


Figure 4. The average waiting times (temporal strategy) at the high (left) and low (right) targets at the start (grey) and end (black) of the each work block. Error bars show the standard deviation between participants.

Table 2. Effects of position (high and low target), work block (six blocks) and time-in-block (early/late) on waiting time ("temporal strategy") and timing errors ("performance").

Factor	Temporal strategy (average waiting time)			Performance (average timing error)		
	df	<i>F</i>	<i>p</i>	df	<i>F</i>	<i>p</i>
Position (high/low)	1.0	24.3	<0.001	1.0	21.9	<0.001
Work block (1–6)	2.7	1.2	0.335	3.8	11.6	<0.001
Time-in-block (early/late)	1.0	1.1	0.306	1.0	1.3	0.264
Position × Work block	2.8	5.2	0.004	3.0	1.5	0.228
Position × Time-in-block	1.0	12.0	0.003	1.0	13.8	0.002
Work block × Time-in-block	2.8	0.6	0.606	3.8	3.9	0.008
Position × Work block × Time-in-block	2.7	1.0	0.410	3.5	2.6	0.050

Notes: Degrees of freedom (df), *F*-values and *p*-values are shown for main effects and interactions. Significant results ($p < 0.05$) are boldfaced.

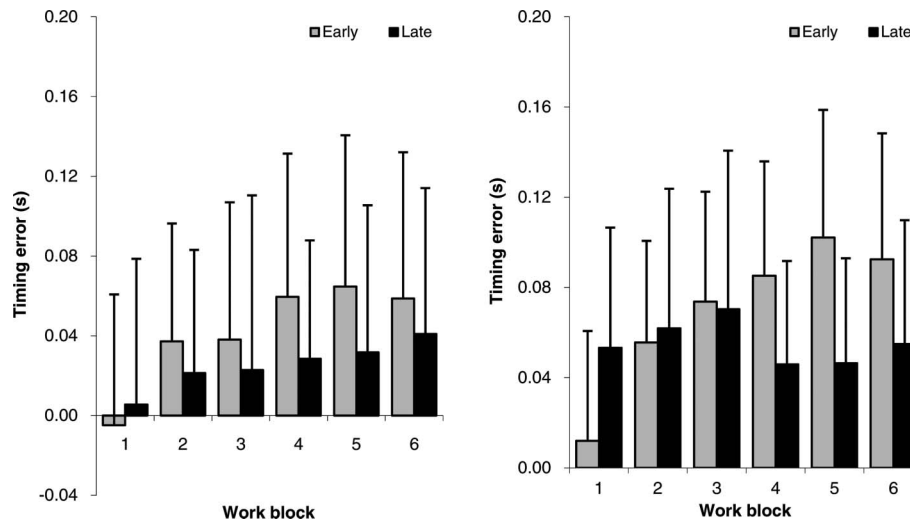


Figure 5. The average timing errors (performance) at the high (left) and low (right) targets at the start (grey) and end (black) of the each work block. Error bars show the standard deviation between participants.

out of 18 participants actually consistently arrived too late at the upper target throughout the one-hour work, while five changed performance from arriving late in the beginning of the first work block to arriving early at the end of the last block. The remaining nine subjects were consistently early on target. A similar inconsistency among subjects was seen for the lower target. Early in the first work block, the cycle-to-cycle variability in timing error was 0.047s at the lower target and 0.041s at the upper. These values did not change significantly within ($p = 0.36$) or across ($p = 0.75$) work blocks.

A borderline significant three-way interaction effect between position, work block and time-in-block was found. Post-hoc testing indicated a significant decrease in timing errors at the upper target (i.e. E1 in Figure 2) while changes in timing error within work blocks for the lower target were inconsistent (i.e. E2 in Figure 2).

Thus, early in the first work block, the average subject started an average cycle by hitting the upper target 0.005s after the metronome beat (E1 in Figure 2), stayed in touch with the upper target for 0.17 s (W1) and hit the lower target 0.012 s ahead of that metronome beat (E2), then staying in touch with the lower target for 0.23 s (W2). Late in the last work block this temporal strategy had changed to an early (0.004 s) arrival at the upper target and a shorter stay at the upper connector (0.15 s). The arrival at the lower connector was 0.09s early, and the waiting time there was now extended to 0.25 s.

3.3. Relationships between changes in EMG levels, EMG variability, temporal strategy and performance

An larger increase in waiting time at the lower connector was significantly correlated ($r = -0.49$) with a smaller increase in EMG levels during downward movements (Table 3). No significant correlation between changes in EMG levels and changes in timing error was found in either movement direction.

A significant negative correlation was also found between changes in EMG variability and waiting time in the downward direction. Furthermore, a larger change in EMG variability was significantly correlated with larger timing errors as shown by the positive correlation coefficients in Table 3.

4. Discussion

In the current study, we investigated changes in temporal motor strategies and performance during series of fatiguing short-cycle repetitive arm movements with interposed rest periods. Furthermore, we explored whether the changes in temporal motor behaviour and performance were associated with changes in muscular responses in the trapezius muscle. Even though the task in the current study was simulated and constrained and the level of exertion was higher than in most repetitive occupational work (e.g. industrial assembly work), it did show similarities with the more strenuous types of short cycle assembly work in a driven production line (Bosch *et al.* 2007) and repetitive pick and place activities (Krawczyk and Armstrong 1991).

4.1. Development of fatigue

All participants developed fatigue during the 1-h work bout, but they differed considerably in fatigue manifestations. One probable reason was that the work load relative to maximal capacity differed between subjects, since they were required to handle the same manipulandum. We found clear signs of increasing fatigue within each work block, both in terms of increased perceived fatigue, and as indicated by a simultaneous increase in EMG amplitude and decline in MPF (e.g. Hägg *et al.* 2000). Over the entire 1-h task we observed a cumulative increase in perceived fatigue and EMG amplitude but not a consistent decrease in the MPF, which is in line with several previous studies which have found that MPF recovery is fast after exercise (e.g. Elfving *et al.* 2002).

4.2. Temporal movement strategy and performance

Participants changed their temporal movement strategy along the bout; the waiting time at the upper target was significantly shortened at the end of the 1-h task. Participants also changed their strategy at the lower target within work blocks; the waiting time was longer at the end of each block. From a biomechanical point of view these are adequate responses to increasing fatigue, since they will reduce the time-averaged shoulder elevation moment produced by the mass of the arm, and thus lower the demand on the upper trapezius muscle. Changes in movement patterns of the upper extremity have been reported after enforced fatigue protocols in several tasks (e.g. Côté *et al.* 2002). Fuller *et al.* (2009), and the authors have suggested that such kinematic changes reflect fatigue adaptation strategies with the purpose of reducing the load on the fatigued body region. In our rather constrained task, changes in the temporal movement strategy also occurred, but this was not sufficient to prevent perceived fatigue and development of fatigue manifestations in the upper trapezius muscle. To this end, it should be noted that in our strictly time-constrained task, the latitude for extending waiting times was limited. This might explain that waiting time did increase within blocks, possibly to the extent feasible, but that no further change was possible across the work blocks through the 1-h work period without compromising performance to an unacceptable level.

Table 3. Pearson correlation coefficients for associations between, on the one hand, changes in EMG amplitude and EMG amplitude variability and, on the other, changes in temporal strategy (waiting time) and changes in performance (timing error).

	Temporal strategy		Performance	
	Up	Down	Up	Down
EMG level up	0.096	-0.223	0.051	0.240
EMG level down	-0.033	- 0.490	0.313	0.318
EMG variability up	0.000	-0.181	0.347	0.485
EMG variability down	0.010	- 0.473	0.548	0.403

Note: Significant correlations ($p < 0.05$) are boldfaced.

Since repetitive work in an occupational setting is usually performed with lower external loads and allows for more temporal and spatial autonomy, e.g. discretionary micro-breaks between consecutive work cycles (Dempsey *et al.* 2010), more flexible cycle times (Möller *et al.* 2004), and alterations in movement trajectories (Möller *et al.* 2004, Madeleine and Madsen 2009), the present findings can only be generalised to 'true' working life with due caution.

A significant decrease in performance was found after 1 h of repetitive work. As indicated by the positive error values (cf. Figure 5), participants reached on average both targets too early, most pronounced for the lower target. This might be explained by the shorter waiting time at the upper target: participants started their downward movement earlier and as a consequence of that arrived at the lower target too early. This seems to be supported by the on average 0.08s longer waiting times at the lower target.

In the upward movement direction, the gradually longer waiting times at the lower target within each work block did not result in hitting the upper target too late, as indicated by the positive error values. Participants showed a significant decrease in timing error at the upper target within work blocks. This apparent improvement of performance seems to a large extent to be a consequence of hitting the target too early at the beginning of each work block, yet more exact in time late in the block.

4.3. Relationships between changes in temporal strategy, performance and muscle activity

While EMG levels generally increased over time, suggesting that the subjects were forced to engage more motor units in performing the task (Hägg *et al.* 2000), this change, as well as the change in EMG variability was negatively associated with changes in the temporal motor strategy. This might indicate that those participants developing a strategy with, on average, longer waiting times during work managed to, to some extent, maintain a more stable motor solution than those with less changes in temporal strategy. Notably, the average change in waiting time was accomplished without loss of consistency in timing, as shown by the stable values of cycle-to-cycle variability in waiting time within and across work blocks. Even performance was negatively correlated to changes in EMG, which suggests that a more stable motor solution promotes better performance. Gates and Dingwell (2008) studied temporal changes in timing error during sawing till exhaustion. No significant reduction in performance was found although a trend towards a larger average timing error and more inter-individual variation might indicate reduced performance in some participants.

The focus of the current study was on changes in temporal strategy and performance and their possible relationships with loading of the trapezius muscle. Obviously, more kinematic measures (e.g. Gates and Dingwell 2010; Fuller *et al.* 2011) would have provided an opportunity to understand in detail the kinematic adaptations underlying the temporal changes observed in the present study.

Although the upper trapezius muscle is generally considered to be a particular important muscle when studying exposure and disorders in the shoulder region, it cannot be ruled out that other shoulder muscles responded differently to the repetitive task and thus would have an influence on or relationship with the temporal strategy. Earlier studies showed that a changed load sharing between synergistic muscles in the shoulders and neck can occur (Palmerud *et al.* 1995), and even a spatial redistribution within the trapezius muscle (e.g. Falla and Farina 2007). Since, to our knowledge, no studies have so-far investigated the effects of a changed temporal movement strategy on the relative engagement among and within shoulder muscles in repetitive occupational work, this might be an interesting issue for further research.

In conclusion, the temporal movement strategy changed within and across work blocks during highly repetitive and fatiguing work. These changes in temporal strategy were accompanied by changes in performance and muscle activity. Although the current study could not determine the causal relationship between these changes, the results suggest a relationship between fatigue development, altered timing, muscle activation strategies and performance.

4.4. Practical conclusions

The current study showed that the movement strategy while performing a prolonged repetitive task may change, possibly for the purpose of alleviating fatigue, but also that the change may not be sufficient to eliminate fatigue. It might be hypothesised that the current constrained task did not allow for sufficient motor variability to effectively counteract fatigue. Whether occupational settings, e.g. in industrial assembly, offer such opportunities to a wider extent, and whether such opportunities would then be utilised by the employees is an interesting issue for further research.

The current study also demonstrated that performance may decrease during prolonged repetitive tasks. The performance indicator used in this study was timing error. While relatively small, errors of the present size might

still have serious consequences in occupational settings requiring great accuracy and not offering opportunities to repair errors. Examples are standardised short-cycle line assembly and environments requiring very strict work procedures due to extreme quality demands, such as in medical equipment manufacturing plants (e.g. catheter assembly). In these work situations adjustments in motor behaviour for the purpose of avoiding such errors may not be practicable, and thus fatigue may increase at a greater rate.

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